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Evaluation of the capability of accepting large-scale wind power in China

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ABSTRACT

With regard to energy conservation and the reduction of emissions, China is dedicated to facilitating the development of renewable energy in order to fulfil its international responsibility. In recent years, the installed wind power capacity in China has increased rapidly due to its large scale and centralization. The high penetration of wind power has brought about a series of problems such as the wind energy utilization and curtailment, auxiliary services and the pricing mechanism. The resolution of these problems needs policies which will provide more support than the current technologies and standards for wind power. This paper takes the evaluation of capability of accepting large-scale wind power in China as its object of study. According to the analysis of such risk factors as the influence of the grid on wind power integration, wind power itself, the market and policy, an evaluation model of the ability of accepting large-scale wind power is established based on risk theory. Then, the estimation of the ability to accept wind power in Gansu Province is used to testify to the effectiveness of this model. Finally, a series of reasonable policies for wind power are proposed.

Contents

1. Introduction

With economic development and the improvement of people's living standards, China's energy consumption and supply maintained rapid growth, has been an arduous task for China to save energy and reduce emissions. In 2011, China's total energy consumption, converted into standard coal, was about 3.48 billion

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tons, with a growth of 7.1% compared to 2010; total primary energy production reached 3.18 billion tons of standard coal, and the energy production structure was dominated by raw coal, accounting for 77.8% of total energy production, while non-fossil energy accounted for only 8.8%. During the period of the Eleventh Five-Year Plan (2005 to 2010), China's energy consumption per unit of GDP dropped to 19.1%. Moreover, carbon dioxide emissions per unit of GDP reduced by 1.46 billion tons. According to the Twelfth Five-Year Plan – the National Economic and Social Development Plan of the People's Republic of China (2011 to 2015) – by 2015, the total consumption of non-fossil energy in primary energy consumption will reach 11.4%, with a 16% reduction in energy consumption per unit of GDP, as well as a 17% reduction in carbon dioxide emissions per unit of GDP. To achieve these goals, the Plan proposed, by 2015, installed non-fossil energy generation will account for 30% of total installed generation.

Wind power comprises the largest development and market-oriented utilization of non-hydro renewable resources at this stage, and as of June 2012, China's grid-connected wind power was 52.58 GW. The total installed wind power capacity may reach 70 GW by 2015, according to the Plan, and the annual energy output will be 140 TWh. In the six provinces – Gansu, Xinjiang, Hebei, Jilin, Inner Mongolia, Jiangsu – China have planned to build 7 large 10 GW wind power bases by 2020, with an installed capacity target of 80–100 GW. By 2050, China's total installed capacity of wind power will exceed that of hydropower. Therefore, the study on the capability of accepting large-scale wind power in China is of great practical significance in the process of the rapid growth of installed wind power.

The capability of accepting wind power in this paper is defined as the maximum capacity of the wind power generator connected to the electricity grid to meet the electricity demand in order to guarantee the security and stability of the power system. Researchers have explored the wind integration problem in great depth from the perspective of integration factors, integration technology, integration policy and other issues. Salmank and Teo [1] and Numes and Lopes [2]state that the factors which prevent wind power from penetrating the grid are the galvanic current in the power system, voltage, the stability of wind power, power quality and peak shaving ability etc. The Black and Veatch Corporation [3] point out that the integration of wind power needs additional reserve capacity. As wind speed cannot be predicted with complete accuracy, Hedegaard and Meibom [4] believe that there would be a problem in balancing the power supply and demand if large-scale wind power were merged into the power grid. With regard to the large power system, Billinton and Wangdee [5] find that when large-scale wind power is connected to an area which has poor transmission ability, the transmission limit poses a challenge. Mathiesen and Lund [6] analyse seven kinds of wind power integration technology and point out that heat pump technology is the most promising way to reduce excess power supply; flexible electricity demand and electricity boilers are the least expensive forms of integration technology, while battery-powered cars are the most promising method of integrating wind power. Ekman and Jensen [7] believe that hydrogen storage technology is an effective integration tool for large-scale wind power. In addition, Rombauts and Delarue [8] introduce two methods of reducing the volatility of wind power: one is the cross-border distribution of wind farms in different places, while the other is maintaining an adequate ability to transmit electricity between different countries. Ummels et al. [9] and Tarroja and Mueller [10] state that the international wind power trade is advantageous for wind power integration and that merging wind power from different regions together could reduce the volatility of wind power, thereby stabilising the system frequency. Weigt and Jeske [11] show that High Voltage Direct Current (HVDC) Transmission is the most economical way to integrate large-scale offshore wind power. Haghi et al. [12] suggest the use of the complementary features of wind power and solar power to realise the penetration of renewable energy into power systems. Meanwhile, Hoicka and Rowlands [13] also point out that the partitioning of both wind farms and photovoltaic farms is better than their configuration in one district. In addition to these technical measures, large-scale wind power integration also needs the support of policies and regulations. Lin and Yu [14] show that tax exemption policies, quota policies, subsidies and tariff price policies for wind power could promote the integration of wind power effectively.

Since wind power is intermittent and random, the acceptation of wind power involves a lot of risk. At present, wind power development in China is becoming increasingly large and concentrated, and so ways of identifying and avoiding risks promptly and effectively are particularly important. Therefore, a risk-based model of the evaluation of accepting large wind power for China is needed urgently. Finally, this paper proves the viability of the model by using a case study. The application of this model to assess the risk level of wind power integration, and the ability to accept wind power so that we can carry out the quantitative control for the risk factors, contribute to the realization of two objectives proposed above and the optimization of energy structure in China.

2. Evaluation model of the capability of accepting large-scale wind power

2.1. Analysis of the risk factors influencing wind power integration

The feasibility of the integration of wind power into the power system is influenced mainly by several risk factors relating to the power grid, wind, policy and the market. These factors represented in Fig. 1, include the system load level, system load characteristics, storage capacity, wind power transmission, wind velocity, the accuracy of wind power predictions, low voltage ride through capability of wind turbine, users' awareness of the integration, wind power integration subsidies, wind power pricing mechanisms and wind power integration supervision.

This paper classifies these influential factors into two groups. The first one contains factors relating to the power grid and wind, the effect of which on wind power integration due to different characteristics and conditions is suitable for quantitative analysis. The other one contains policy and market factors, the effect of which on wind power integration is suitable for qualitative analysis and is affected by decision makers' experience and cognitive ability.

2.2. Evaluation model of the capability of accepting wind power based on risk analysis

2.2.1. Mathematical expressions

This paper will establish an evaluation model of the feasibility of wind power integration based on risk. The model contains two parts, the first of which is the theoretical calculation of the feasibility of wind power integration without taking risk into consideration, which could be achieved by realizing the system peak load balance. The second part is adjusted for the feasibility of wind power integration. As the possibility of wind power integration is influenced by two different classifications of risk factors, the second part also contains its two parts, the first of which is the product of the probability of the first group of risk factors and their influence. Accordingly, the other is the influence value due

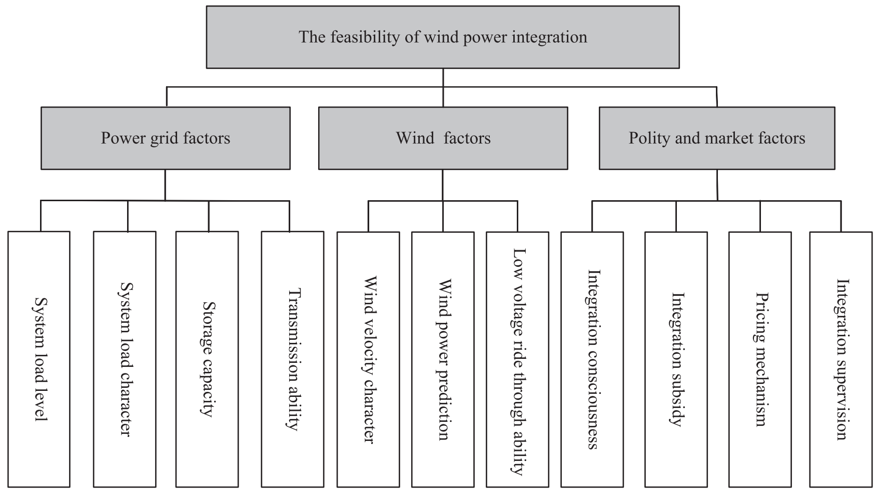

Fig. 1. Factors influencing wind power integration.

to the second group of risk factors. The model is illustrated in Eqs. (1) and (2).

$$P_{iwind} = P_{wind} + P_{awind} \tag{1}$$

$$P_{awind} = \sum_{i=1}^{n} f(xi)Pi + \theta P_{wind} \tag{2}$$

where P_{iwind} represents the actual feasibility of accepting wind power taking into account risk factors, P_{wind} represents the theoretical value of the feasibility of accepting wind power without taking risk into consideration, P_{awind} represents the adjustment value of the feasibility of accepting wind power, P_i represents the probability of the first classification of risk factor i, $f(xi)$ represents its subsequent influence value and θ represents the adjustment coefficient due to the second classification of risk factors.

2.2.2. Calculation of the theoretical value of the ability to accept wind power

2.2.2.1. Definition of the generator combination

(1) Target function

The optimal distribution of the system load should meet both the operational and generator restrictions, which will ensure that both the generating cost and active power loss are minimized. The target functions are illustrated in Eq. (3):

$$\begin{cases} \min f1 = \sum_{i=1}^{NG} Fi(P_{it}) \\ \min f2 = P_{losst} = f(P_{it}) \end{cases} \tag{3}$$

where P_{it} represents the active power of generator i in time interval t, N_G represents the total number of generators in the power system, $F_i(P_{it})$ represents the energy consumption characteristics of generator i in time interval t and Plosst represents the total system active power loss in time interval t.

Usually, $F_i(P_{it})$ is described by the following quadratic function, given as Eq. (4):

$$F_i(P_{it}) = A_i {P_{it}}^2 + B_i P_{it} + C_i \tag{4}$$

where A_i represents the quadratic coefficient of coal consumption curve of generator i, B_i represents the monomial coefficient of coal consumption curve of generator i and C_i represents the constant term of coal consumption curve of generator i.

(2) Constraint conditions

(i) Active power balance constraint

$$\sum_{i=1}^{NG} P_{it} = P_{Lt} + P_{losst} \tag{5}$$

where $\sum_{i=1}^{NG} P_{it}$ represents the total active power of all of the generators in time interval t, P_{Lt} represents the total system load and P_{losst} represents the total active power loss in time interval t.

(ii) Operational constraint

$$P_{it,\min} \le P_{it} \le P_{it,\max} \tag{6}$$

where $P_{it,\min}$ and $P_{it,\max}$ represent the lower limit and the upper limit of the active power from generator i in time interval t respectively.

(iii) Creep speed constraint

$$-\xi_{idown} \le P_{it} - P_{i(t-1)} \le \xi_{iup} \tag{7}$$

where ξ_{idown}.and ξ_{iup} represent the decreasing speed limit and the increasing speed limit of generator i respectively.

2.2.2.2. Calculation of the theoretical value of wind power integration without taking risk into consideration. Under the condition of the confirmed generator combination in the system peak load phase, we can calculate the maximum ability of the system power supply. The calculation formula is illustrated in Eqs. (8)–(10) as follows:

$$P_{\max} = (P_{the} + P_h + P_o - P_{pk})(1 - \delta_{los}) + \eta P_{sto} \pm \{P_{lin}(1 - \delta_{los})\} \tag{8}$$

$$P_{the} = P_{thec}(1 - \delta_{fh} - \delta_{fc})(1 - \delta_{fpla}) \tag{9}$$

$$P_h = P_{hc}(1 - \delta_{hh} - \delta_{hc})(1 - \delta_{hpla}) \tag{10}$$

where $P_{\max}$ represents the maximum ability of the system power supply in the system peak load phase, P_{the} represents the maximum active power from the thermal power generator, P_h represents the maximum active power from the hydropower generator, P_o represents the maximum active power from other generators, P_{pk} represents the reserve capacity of power system, δ_{los} represents the transmission loss ratio, η represents the comprehensive efficiency of different kinds of storage equipment, P_{sto} represents the storage capacity, P_{lin} represents the interconnection plan, P_{thec} represents the thermal power capacity, P_{hc} represents the hydropower capacity, δ_{fh} represents the congestion

ratio of the thermal power generator, δ_{hh} represents the congestion ratio of the hydropower generator, δ_{fc} represents the maintenance ratio of the thermal power generator, δ_{hc} represents the maintenance ratio of the hydropower generator, δ_{fpla} represents the power consumption rates of thermal power plant and δ_{hpla} represents the power consumption rates of hydropower plant.

Under the condition of the confirmed generator combination in the system valley load phase, we can calculate the minimum ability of the system power supply. The interconnection participates in the system peak shaving, and the content embodied in the brace exists when the electricity import appears. The calculation formula is illustrated as Eq. (11) as follows:

$$P_{\min} = (P_{thel}+P_{hl}+P_{ol})(1-\delta_{los})-P_{sto}+\{\beta P_{lin}(1-\delta_{los})\} \tag{11}$$

where $P_{\min}$ represents the minimum ability of the system power supply in the system valley load phase, P_{thel} represents the minimum active power from the thermal power generator, P_{hl} represents the minimum active power from the hydropower generator, P_{ol} represents the minimum active power from other generators and β represents the shaving ratio of the interconnection.

We can obtain the theoretical value of wind power integration without taking risk into consideration after three stages. First, we calculate the difference between the maximum ability of the system power supply in the system peak load phase and the minimum ability of the system power supply in the system valley load phase. Second, subtract the maximum difference between peak and valley load from this difference. Finally, we convert the result according to the simultaneity of wind farms. The calculation for the theoretical value of wind power integration without taking risk into consideration is illustrated in Eq. (12) as follows:

$$P_{wind} = \frac{\min\{P_{\max}-P_{\min}-\varepsilon P_{L\max}\}}{\lambda} \tag{12}$$

where P_{wind} represents the theoretical value of wind power integration without taking risk into consideration, λ represents the simultaneity of wind farms in a specific region, ε represents the forecasted value of system peak-valley ratio, $P_{L\max}$ represents the forecasted value of system maximum load.

The calculation procedure for the theoretical value of wind power acception without taking risk into consideration is shown in Fig. 2.

2.2.3. Probability distribution analysis for the first group of risk factors

(1) System load risk

It is impossible to predict accurately future system load, and the prediction errors for the system load and the difference between peak and valley load usually obey normal distribution. At present, prediction accuracy has reached 95%–98%. Therefore, in this paper, the prediction errors for the system load and the difference between peak and valley load obey the normal distribution, the mean value of which is 0 and the variance of which isσ. Theσvalue is derived from an analysis of the historical data of the system load level and the difference between peak and valley load. The probability density curve of the system load risk is illustrated in Fig. 3.

(2) Storage capacity risk

The storage technique is an important method of integrating wind power. With the increasing penetration of wind power into the power system, the greater the scale of the storage capacity, the greater the acceptance of wind power. The storage capacity of the system is determined primarily by the economy of energy storage devices.

This paper supposes that triangular distribution is suitable for the storage capacity risk, and that the coefficients x_a, x_b and x_c are determined by the possible minimum value of storage capacity risk, the possible average value of storage capacity risk and the possible maximum value of storage capacity risk, respectively, after predicting the economics of storage capacity. The probability density curve of the storage capacity risk is illustrated in Fig. 4.

(3) Transmission risk

Large-scale sources of wind power are usually far from the load centre, and so it is necessary to transport the wind power through a long electric transmission line. When transmission congestion occurs, the power system must decrease the penetration of wind power, which will significantly restrict the feasibility of wind power integration. Therefore, we use the transmission congestion ratio to describe the transmission risk. The transmission congestion ratio is that, when the line congesting, planned transmission capacity minus line total transmission capacity, then the result is divided by planned

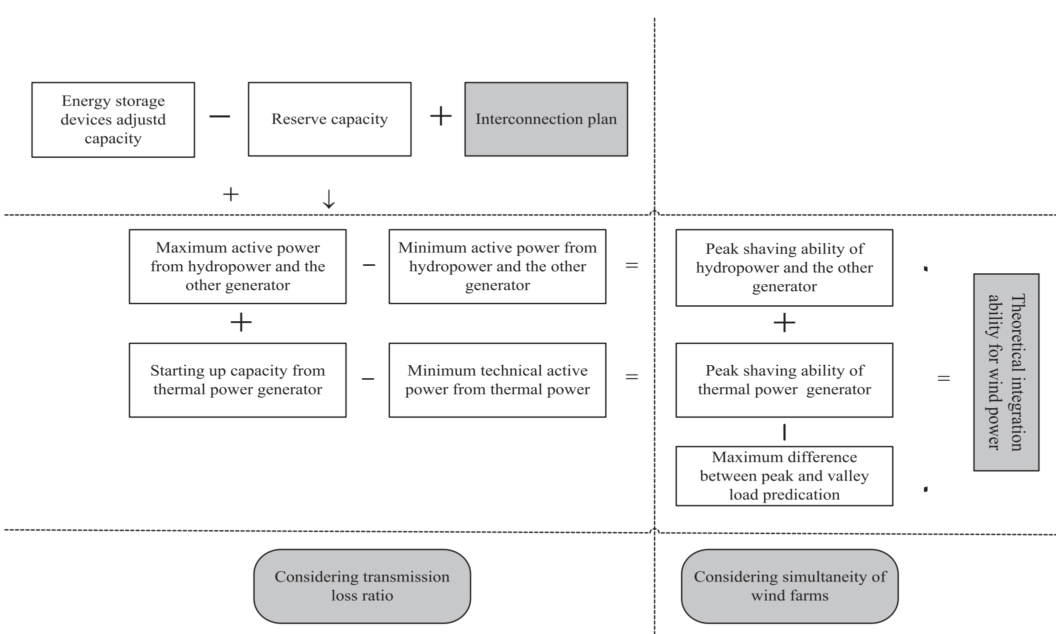

Fig. 2. Calculation procedure for theoretical acception ability.

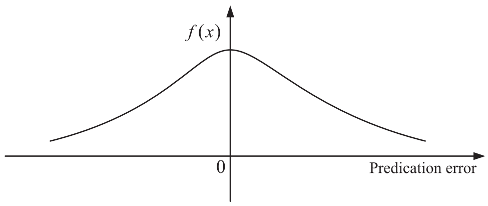

Fig. 3. Probability density curve of system load risk.

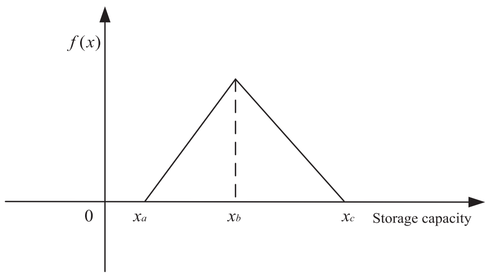

Fig. 4. Probability density curve of storage capacity risk.

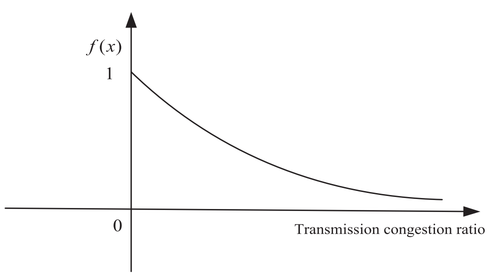

Fig. 5. Probability density curve of transmission risk.

transmission capacity. This paper believes that the transmission congestion ratio approximately obeys the pattern of exponential distribution, and that the coefficient λ is determined by the average transmission congestion ratio. The probability density curve of transmission risk is illustrated in Fig. 5.

(4) Wind power side risk
Global climate change makes it more difficult to predict the future wind velocity; wind power fluctuations and randomness affect the accurate prediction of wind power directly; a low-voltage ride through the capability of a wind turbine is also an important factor which affects the wind power output. Wind power side risk has a direct impact on simultaneity of wind farms which are centralized development.
This paper believes that triangular distribution is suitable for the wind power side risk, and that the coefficients x_a, x_b and x_c are determined by the historical minimum value of the simultaneity of wind farms, their historical average and historical maximum value. The probability density curve of the wind power prediction risk is illustrated in Fig. 6.

2.2.4. Definition of the influence value of the first group of risk factors

(1) System load level risk
Under the current power source structure, the system maximum load prediction value could determine the generator combination and therefore influence the feasibility of wind power integration by changing the system's peak shaving ability. Its influence value function is illustrated in Eq. (13) as

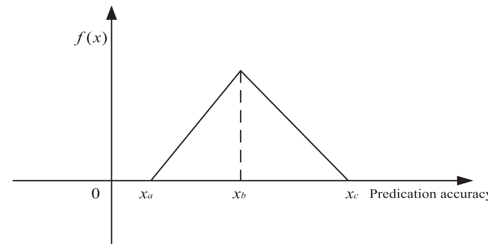

Fig. 6. Probability density curve of wind power prediction risk.

follows:

$$f(\Delta P_{L\max}) = -\frac{\varepsilon}{\lambda}\Delta P_{L\max} \tag{13}$$

where $f(\Delta P_{L\max})$ represents the influence value due to the system load level risk, ε represents the forecasted value of system peak-valley ratio, λ represents the simultaneity of wind farms and $\Delta P_{L\max}$ represents the system maximum load change.

(2) Load character risk
Under the current power source structure, the difference between the peak and valley loads will influence the feasibility of wind power integration. The greater the difference, the lower the feasibility of wind power integration. Its influence value function is illustrated in Eq. (14).

$$f(\Delta\varepsilon) = -\frac{\Delta\varepsilon}{\lambda}P_{L\max} \tag{14}$$

where $f(\Delta\varepsilon)$ represents the influence value due to the load character risk, $\Delta\varepsilon$ represents the change in system peak-valley ratio, λ represents the simultaneity of wind farms and $P_{L\max}$ represents the forecasted value of system maximum load.

(3) Storage capacity risk
Storage capacity influences the feasibility of wind power integration – more storage capacity increases the feasibility of wind power integration. Its influence value function is illustrated in Eq. (15) as follows:

$$f(\Delta P_{sto}) = \frac{(1+\eta)}{\lambda}\Delta P_{sto} \tag{15}$$

where $f(\Delta P_{sto})$ represents the influence value due to the storage capacity risk, η represents the comprehensive efficiency of different kinds of storage equipment, λ represents the simultaneity of wind farms and ΔP_{sto} represents the change in storage capacity.

(4) Transmission risk
When the local wind power integration ability is saturated, the strategy of transmitting the excess wind power to other provinces is the best strategy. The greater the amount of power transported, the greater the potential for wind power integration. Its influence value function is illustrated in Eq. (16) as follows:

$$f(\Delta E_c) = -E_c P_{wind} \tag{16}$$

where $f(\Delta E_c)$ represents the influence value due to transmission risk, E_c represents the transmitting congestion ratio.

(5) Wind power side risk
When wind energy utilization efficiency of wind farms improved, the simultaneity of wind farms will increase, resulting in a decrease in the accepting of wind power. In the long run, its influence value function is illustrated in Eq. (17) as follows:

$$f(\Delta\lambda) = -\frac{\Delta\lambda}{\lambda+\Delta\lambda}P_{wind} \tag{17}$$

where $f(\Delta\lambda)$ represents the influence value due to the wind power side risk, $\Delta\lambda$ represents the change in the simultaneity of wind farms.

2.2.5. Method for the definition of the influence value of the second group of risk factors

In the early days, the lack of wind power was related to policy and the market, and wind power was mainly integrated within local areas. Under the conditions specified by the fixed first classification of risk factors, the second classification of risk factors, which are both policy- and market-related, restrict the ability to integrate wind power. This is because both policy and markets usually behave in an "out of place" state, during of which it is necessary to eliminate the faulty aspect of both policy and markets and improve them continuously. With the development of both policy and markets, if both of them reach the "in right place" state, the restrictions they have imposed will decrease significantly, and the potential for wind power integration will increase by a large margin. Once both policy and the market are "in right place," albeit in a state of continuous development, the promotion of the ability to integrate wind power will not work as well as in the previous stage, and high costs will be incurred, then "in excess place" appears. Therefore, this paper defines "in right place" as the optimal state for promoting wind power integration. We can judge the current state of both policy and the market with the help of experts' experience, statistics and comparative analysis.

This paper uses a θ value which could describe the different states of both policy and the market: $\theta=0$ represents "in right place," $\theta<0$ represents "out of place" and $\theta>0$ represents "in excess place". The θ value is obtained when experts consider integration awareness, integration subsidies, pricing mechanisms and integration supervision. The distribution curve of the θ value is illustrated in Fig. 7.

3. Case study

3.1. Overview

Gansu Province is one of the provinces of China with an abundance of wind energy resources. Its theoretical reserves of wind resources are 237 GW and approximately 40 GW of which can be developed. Jiuquan in the Gansu Province is south of the Qilian Mountains, and north of the North Mountains. Therefore, it has the favourable terrain of a valley between two mountains, which forms a wind channel that is rich in wind resources, with the ideal conditions for exploring a large-scale wind power base. Against the background of the national energy conservation policy, the Gansu Province has a good opportunity to develop wind power.

According to Gansu power grid's main network plan for the period of the Twelfth Five-Year Plan (2011 to 2015), the installed capacity of centrally dispatched power in Gansu power grid will reach 46.04 GW in 2015, including 9 GW of hydropower, 23.9 GW of thermal power, 12.84 GW of wind power and 0.3 GW of solar power, as shown in Table 1.

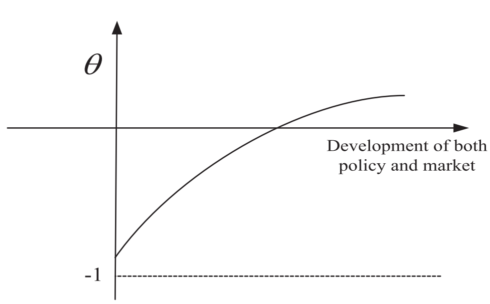

Fig. 7. Distribution curve of the θ value.

Table 1
The installed capacity plan in Gansu Power Grid Unit: GW.

Items	Year 2015
Installed capacity of thermal power	23.90
Installed capacity of hydropower	9.00
Installed capacity of wind power	12.84
Installed capacity of solar power	0.30
Total	46.04

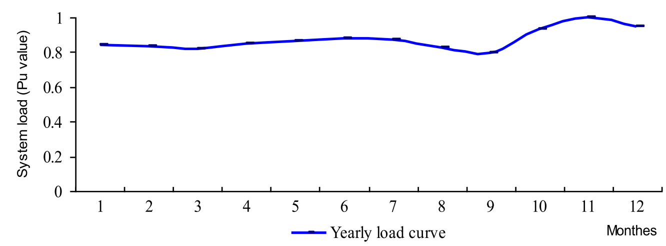

Fig. 8. Typical annual load curve in Gansu power grid.

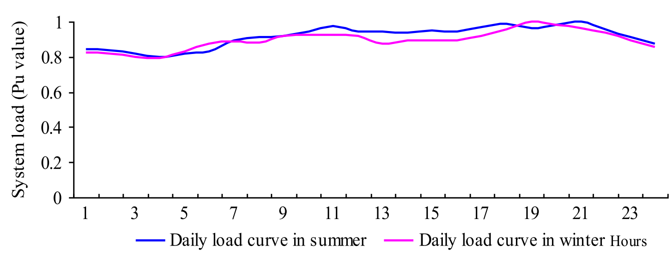

Fig. 9. Typical daily load curve in Gansu power grid.

The regular pattern of annual load variation in Gansu power grid is that the load in winter and the agricultural irrigation season during May to July is higher, while the load is lower during other months. The annual peak load occurs mainly in November, while the valley load occurs mainly in September, as shown in Fig. 8.

There are two peaks in the daily load variation which appear in the morning and in the evening, and the peak load in the evening is higher. In winter, the peak load arrives at 19:00, while the valley load arrives at 4:00. In summer, the peak load appears at 21:00, while the valley load appears at 4:00, as shown in Fig. 9.

3.2. Analysis and evaluation of the factors influencing wind power acception

(1) Analysis and evaluation of system load risk
During the period of the Eleventh Five-Year Plan (2006 to 2010) in China, the system load and the difference between the peak and valley load in Gansu power grid grew steadily, and the prediction accuracy rate was above 97%. With the implementation of the policy which states that the national key industry must transfer to the Northwest of China, the energy-intensive industry in Gansu Province will develop more rapidly. Consequently, the system load and the difference between the peak and valley loads will be harder to

predict. We judge that during the period of the Twelfth Five-Year Plan, the prediction accuracy rate of the system load and the difference between the peak and valley loads in Gansu power grid is more likely to be 96%. The possibilities of these are likely to be 0.921 and 0.877, respectively. Therefore $\Delta P_{L\max}=(1-96\%)P_{L\max}$, $\Delta\varepsilon=(1-96\%)\varepsilon$, the influence value due to the system load level risk and the load character risk respectively are:

$$P(\Delta P_{L\max}) = 0.921 \times \left(-\frac{\varepsilon}{\lambda}\Delta P_{L\max}\right) \tag{18}$$

$$P(\Delta\varepsilon) = 0.877 \times \left(-\frac{\Delta\varepsilon}{\lambda}P_{L\max}\right) \tag{19}$$

(2) Analysis and evaluation of storage capacity risk
The main energy storage technologies which may potentially be used in Gansu Province are pumped storage, heat pumps, electric boilers, hydrogen storage, storage batteries, etc. However, because of the weak economic foundations in Gansu Province, large-scale usage of these energy storage technologies is unlikely. During the period of the Eleventh Five-Year Plan, the basic energy storage capacity in Gansu power grid was small. According to comprehensive judgments, during the period of the Twelfth Five-Year Plan, the energy storage capacity in Gansu power grid will be approximately 0.5 GW–1 GW. Considering the new storage equipment needs more time and money to be built, the possibility of this event is likely to be 0.891. Therefore, $\Delta P_{sto}=0.5$ GW, the influence value due to the storage capacity risk is:

$$P(\Delta P_{sto}) = 0.891 \times \frac{(1+\eta)}{\lambda}\Delta P_{sto} \tag{20}$$

(3) Analysis and evaluation of transmission risk
In order to meet the demands of the rapid growth in the wind power installed capacity, Gansu Province has re-planned its wind power transmission channel, e.g. through the 800 kV HVDC transmission lines from Jiuquan in Gansu Province to Zhuzhou in Hunan Province. During the period of the Twelfth Five-Year Plan, the wind power transmission channels will be accomplished one by one, and the transportability of wind power will be significantly improved. At present, due to the limited transmission ability of Gansu power grid, it is difficult for wind power to be dispatched and the transmission congestion is significant. However, during the period of the Twelfth Five-Year Plan, the average rate of transmission congestion in Gansu power grid will be reduced, and is likely to be as low as 5%. The possibility of this event is likely to be 0.885. Therefore, $\Delta E_c=0.5$, the influence value due to the transmission risk is:

$$P(\Delta E_c) = 0.885 \times (-E_c P_{wind}) \tag{21}$$

(4) Analysis and evaluation of wind power side risk
In the short term, the risk of wind power side is small. However, because wind power prediction technology and the performance of wind turbines continue to improve, the simultaneity of wind farms in the period of the Twelfth Five-Year Plan will increase substantially. After comprehensive judgment, it will probably be around 70% during the period of the Twelfth Five-Year Plan. The possibility of this event is likely to be 0.825. Therefore, $\Delta\lambda=0.7-\lambda$, the influence value due to the wind power risk is:

$$P(\Delta\lambda) = 0.825 \times \left(-\frac{\Delta\lambda}{\lambda+\Delta\lambda}P_{wind}\right) \tag{22}$$

(5) Analysis and evaluation of policy and market risk
With the comparative analysis the four factors which include the users' awareness of integration, the pricing mechanism of wind power, subsidies for wind power integration and the supervision of wind power integration, it is obvious that both the current market and policy in Gansu Province are not "in right place." With the accomplishment of 10 GW wind power farms in Gansu Province, the state will continue to support them through policy. Through the coordination of interests among market participants, both the policy- and market-related factors that restrict wind power integration will gradually diminish. Experts predict that the θ value will lie between -0.15 and -0.05 during the Twelfth Five-Year Plan periods.

3.3. Analysis of the ability to accept wind power in Gansu province

Thermal power and hydropower are the main power resources in Gansu Province, and these two resources are both controllable. However, due to the rapid increase in the wind power installed capacity, the system's ability to integrate wind power will be significantly affected, especially when the peak shaving ability of hydropower is weak during the summer. The theoretical value of the ability to integrate wind power in different operational modes (such as a low load in summer, a high load in summer, a low load in winter and a high load in winter) during the Twelfth Five-Year Plan has been calculated according to the calculations presented above. Finally, considering the risk factors, this paper estimates the adjusted value of wind power integration. The outcomes are shown in Table 2.

As shown in Table 2, the Gansu power grid cannot integrate all of the wind power installed capacity. A total of 9.21 GW of wind power installed capacity could not be integrated in Gansu Province in 2015.

3.4. Sensitivity analysis

In 2015, the actual amount of wind power that could be integrated in Gansu Province was 3.47 GW. Considering the effect of both the first and second groups of risk factors, we conducted a sensitivity analysis of the actual feasibility of wind power integration in Gansu Province in 2015, as is shown in Fig. 10.

Fig. 10 shows that the first group of risk factors, which includes the system load level, the difference between the peak and valley loads, the energy storage capacity, transmission, the fluctuation of the wind velocity and the accuracy of wind power prediction, affects the amount of wind power which can be integrated in Gansu Province more significantly than the second group of risk factors.

Table 2
Feasibility of the integration of wind power in Gansu Province Unit: GW.

Mode	Year 2015
Low load in summer	3.62
High load in summer	3.99
Low load in winter	6.14
High load in winter	6.09
Theoretical integration ability	3.62
Adjusted integration ability	−0.17
Actual integration ability	3.45

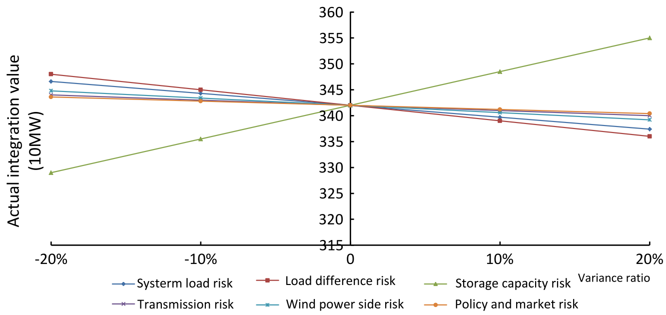

Fig. 10. Sensitivity analysis of the ability to accept wind power.

4. Conclusions

This paper concludes that it is necessary to consider risk factors when designing the plan for the integration of large-scale wind power. We have put forward a risk evaluation index system for large-scale wind power integration. In addition, the actual ability to integrate wind power should be divided into two parts: one is the theoretical value and the other is the adjusted value when the ability to integrate wind power is calculated for a specific region. The integration of large-scale wind power is a comprehensive system including five stages: power generation; power transmission; power transformation; power dispatching and power consumption. With the aim of helping to resolve the problem of accepting large-scale wind power in China, this paper proposes the following suggestions:

(1) The means of wind power acception in the local area should be actively explored, such as the development of the energy storage system, the development of electric vehicle and the appropriate development of the inter-provincial acception of wind power.
(2) The power grid and the power source must be planned with synchronous development, and the amount of wind power should be controlled according to the power grid, adjusting the power grid plan rationally, according to the development of wind power, thus leading to a coordinating mechanism between wind power and the power grid.
(3) Energy plans should be made to favour the transmission of wind power between different areas. Wind power acception policy should be made at national level, and should set an appropriate low-carbon energy quota for each province, according to the amount of primary energy obtained from other areas.

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References

[1] Salman SK, Teo ALJ. Windmill modeling consideration and factors influencing the stability of a grid-connected wind power-based embedded generator. IEEE Transactions on Power Systems 2003;18(2):793–802.
[2] Nunes MV, Lopes JAP. Influence of the variable-speed wind generator in transient stability margin of the conventional generators integrated in electrical grids. IEEE Transactions on Energy Conversion 2004;19(4): 692–701.
[3] Economic Impact of Renewable Energy in Pennsylvania. Black and Veatch Corporation; 2004.
[4] Hedegaard K, Meibom P. Wind power impacts and electricity storage – a time scale perspective. Renewable Energy 2011;37(12):318–24.
[5] Billinton R, Wangdee W. Reliability-based transmission reinforcement planning associated with large-scale wind farms. IEEE Transactions on Power Systems 2007;22(1):34–41.
[6] Mathiesen BV, Lund H. Comparative analyses of seven technologies to facilitate the integration of fluctuating renewable energy sources. IET Renewable Power Generation 2009;14(3):190–204.
[7] Ekman CK, Jensen SH. Prospects for large scale electricity storage in Denmark. Energy Conversation Management 2010;51(6):1140–7.
[8] Rombauts Y, Delarue E. Optimal portfolio-theory based allocation of wind power: taking into account cross border transmission capacity constraints. Renewable Energy 2011;36(8):2374–87.
[9] Ummels BC, Pelgrum E, Gibescu M. Comparison of integration solutions for wind power in the Netherlands. IET Renewable Power Generation 2009;23(6): 279–92.
[10] Tarroja B, Mueller F. Spatial and temporal analysis of electric wind generation intermittency and dynamics. Renewable Energy 2011;36(12):3424–32.
[11] Weigt H, Jeske. T. Take the long way down: integration of large-scale North Sea wind using HVDC transmission. Energy Policy 2010;38(9):3164–73.
[12] Haghi HV, Bina MT, Golkar MA. Using copulas for analysis of large datasets in renewable distributed generation: PV and wind power integration in Iran. Renewable Energy 2010;35(6):1991–2000.
[13] Hoicka CE, Rowlands. IH. Solar and wind resource complementarity: advancing options for renewable electricity integration in Ontario, Canada. Renewable Energy 2011;36(5):97–107.
[14] Lin CJ, Yu OS. Challenges of wind farms connection to future power systems in Taiwan. Renewable Energy 2009;5(34):1926–30.